UNIVERSITÉ DE MONTRÉAL

CENTRE DE RECHERCHE SUR LES TRANSPORTS

CASE POSTALE 6128, SUCCURSALE A, MONTRÉAL, QUÉBEC, H3C 3J7

OPERATIONS RESEARCH MODELS OF INTERCITY FREIGHT TRANSPORTATION : THE CURRENT STATE AND FUTURE RESEARCH ISSUES

by

Teodor Gabriel Crainic

This research has been supported in part by a grant from Transport Canada through the Transport University Programs.

Cette étude a été publiée grâce à une subvention du fonds F.C.A.R. pour l'aide et le soutien à la recherche.

Paper published in The Logistics and Transportation Review 23(2), 189-206, June 1987.

Université de Montréal
Centre de recherche sur les transports - Publication #499
Décembre 1986

Dépôt légal - 3e trimestre 1987

ABSTRACT

Various operations research models are reviewed and promising research opportunities are outlined for two major fields of intercity freight transportation study : predictive analysis of the multimodal system and the planning of transportation services.

Key words : intercity freight transportation, multimode, predictive analysis, transportation service planning, strategic/tactical planning

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RÉSUMÉ

Nous passons en revue des modèles de recherche opérationnelle et nous dégageons des avenues de recherche intéressantes pour deux aspects majeurs du transport interurbain de marchandises : l'analyse prédictive du système multimodal et la planification des services de transport.

Mots clés : transport des marchandises, services multimodes interurbains, analyse prédictive du système, planification des services, planification stratégique/tactique

I - INTRODUCTION

Freight transportation has always been an important economic activity, playing a central role in regional and national economic growth and development and being a vital link in the logistic chain through which raw materials and finished products move. Recently, however, interest in the study of various freight transportation problems aimed at the development of quantitative analysing and planning tools, has greatly increased for several reasons.

Thus, higher energy and labor costs have significantly increased transportation costs which now represent a higher percentage of the costs of finished goods than previously. Also, high interest rates, which have increased inventory costs, and the foreign competition have generated interest in inventory reducing methods such as "just-in-time" production planning. Such methods, however, require reliable and fine-tuned transportation services and, thus, quality of service becomes an important decision criterion. Deregulation of various components of the transportation industry has also resulted in a broader spectrum of options becoming available to the user of transportation services, a larger choice of market opportunities for suppliers of these services, and a higher level of competition in the industry. On the other hand, deregulation policy decisions require studies and analyses to attempt to predict their impact on the transportation system's performances.

Operations research offers powerful and interesting methodologies and techniques to model, analyse and build tools to help solve transportation problems. This has been already amply demonstrated in the field of passenger transportation and, finally, researchers are also showing increased interest in both the theoretical and applied aspects of freight transportation. This is partially motivated by the interest demonstrated by industry and governments. But it also originates in a growing awareness

that passenger transportation (especially urban passenger transportation) is a field which has attained a certain maturity, while freight transportation, a relatively regulated field until now, presents many interesting unsolved problems. In addition, recent advances in computer technology, computer science methods and operation research methodologies and techniques, have enabled larger and more complex problems to be tackled and solved.

Freight transportation is a vast and complex field which may be examined from several points of view and which also intersects other domains such as marketing, production planning, facility location, physical distribution, logistics, national and regional planning. This paper focuses on problems related to the modeling, analysis and planning of intercity freight movements at the tactical and strategic level using operation research methodologies. Its scope is to review the major works accomplished in the area, to bring together the actual research trends, and to point out interesting research perspectives.

Intercity freight transportation encompasses many problems and involves many actors with different means and objectives : consumers and producers of goods, shippers who contract carriers to move raw materials to plants and finished products from plants to markets, governments who supply most of the transportation infrastructure and also monitor, regulate and tax transportation activities, etc. Several products and modes of transportation are usually considered, and decisions must be made concerning network and service design, service levels, freight itineraries, flows, prices and market shares. Decision criteria include economics (usually cost minimisation) of course, but also transportation time and reliability.

It is obvious that no single formulation can encompass all problems, represent all actors, or answer all questions in intercity freight

transportation. Also, the field is so vast and complex that no single paper could possibly cover it all. Our focus is on models aimed at evaluating scenarios and assisting the decision-making process at tactical and strategic planning levels. Generally speaking, these models take a global, aggregated, often schematic, view of the transportation system and are centered on the estimation of the commodity and, eventually, service flow distributions over the transportation network, given the specification of the actors, of their behavioral rules and of their relationships. We class these models into two groups : predictive traffic models that consider several actors (carriers, shippers, ...) in a region, and service design models addressing the case of a specified transportation organization. We examine these models in the following two sections. We also mention, when possible, recent survey papers covering areas of study related to the subject at hand but not examined in detail here.

II - PREDICTIVE MODELS

These are models which attempt to describe the individual decisions of and interactions between shippers and carriers in order to predict flow distributions, prices, market-shares, etc. Such models are important to the understanding of the freight transportation system in a given region or country and, as such, may be used either as part of global economic regional or national studies or, on their own, by carrier companies to predict the responses of shippers and the other carriers to modifications in tariffs and service levels. They may also be used by governments to assess the impact on the transportation system of various regulations, infrastructure modifications, of forecasted economic environment evolution, etc.

Most of these models are so called "network" models where the network structure of the transportation system is explicitly considered in a more or less aggregated form and the distribution of flows on that network reflect and are used to quantify the decisions of the individual

players in the system. Network models may be further divided into two classes according to the optimization principle used. Traffic equilibrium, or user-optimizing, models are descriptive formulations where flows result from the individual decisions of each user toward optimizing his own route choice. System-optimizing models are normative formulations, which suppose the existance of a general goal (e.g., minimize total travel cost), and optimize the flow distribution accordingly. Both types of models are based on behavioral assumptions stated by Wardrop (1952) and extensively used ever since (Florian, 1983). Friesz, Tobin and Harker (1983) did an earlier review of this class of models.

2.1 Literature review

The Harvard model, developed by Roberts (1966) and Kresge and Roberts (1971), was the first significant multimodal predictive freight network model. Developed for a developing country (Colombia) and embedded into a macroeconomic model, the transportation network has cities and regions as nodes and modal routes (highways, rail, air, water) as links. Constant unit origin to destination perceived shipping costs are used to compute shortest paths on the intermodal network. These shortest paths are then used to compute O/D flows and to assign them to the links of the network. Backhaul trips are added afterwards on the same routes as the forehaul trips. The role of carriers and congestion phenomena are ignored in this model.

The Transportation Network Model developped by CACI Inc (see CACI, 1980; Bronzini, 1980a,b) as part of the National Energy Transportation Study is a fixed demand, multimodal freight network model that works on the following assumptions :

1) freight routes are exclusively decided by shippers on minimum cost criteria;
2) the cost of a path is a linear combination of transportation cost, time and energy.

In the original version, commodities are sequentially assigned to a capacitated network, with the assignment dependent on the loading sequence. A more recent version uses an equilibrium assignment, but it is essentially a single-commodity formulation which considers aggregate instead of commodity-specific cost functions. Again, carrier decisions and characteristics are ignored in the formulation.

Another group of models, including the Princeton railroad network model (Kornhauser et al., 1979), the rail freight traffic assigment model (Lansdowne, 1981) and the rail carrier-route choice model (Bronzini and Sherman, 1983), are single-mode (rail) network formulations for predicting the routing of freight through the combined networks of several carriers. The routes are generally computed as intercarrier shortest paths where various measures (cost, time) are included in the cost functions and high impedances are assigned to intercarrier transfers. Generally, backhauling is not addressed in these models and commodities are sequentially loaded.

The freight network equilibrium model (Friesz, Gottfried and Morlok, 1986) explicitly treats the decisions of shippers and carriers on a multimodal freight network with nonlinear costs and delay functions modeling congestion phenomena. It is a sequential model composed of :

1) A shipper submodel : an elastic demand, user-optimizing trip distribution assignment model on an aggregated "shipper-perceived" network.

2) A linking module.

3) A carrier submodel : each carrier is assumed to be an individual operating-cost minimizer, optimizing its network under fixed demand assumptions.

No intercarrier interactions are considered, and carriers are assured not to react to shipper decisions. Backhauling is treated through adjustments to costs and delays.

The multicommodity intermodal transportation network model (McGinnis et al., 1981; Sharp, 1979; Sharp and Jones, 1981) was developed as a tool for the analysis of multimodal freight transportation opportunities for the economic development of the Multi-State Transportation Corridor. It is an explicit multimodal, system-optimizing, network model. Using transportation (carrier) costs, time and time variability, shortest paths (one intermodal and one for each mode) are computed and used to distribute the flow. This model does not explicitly consider either carriers or shippers. Service and congestion phenomena are ignored, costs are linear, and backhauling is not considered.

Harker and Friesz (1982) have proposed a formulation which attempts to take into account the simultaneity of shipper and carrier decisions. Shippers are represented as user-optimizers, employing delivered price, through a set of nonlinear, nonconvex constraints defined in terms of path variables. Carriers are represented as individual operating-cost minimizers. Intercarrier interactions are not considered. The presence of the specific constraints of the shipper formulation and their implications (i.e. nonconvexity and the need to enumerate paths) results in a complex mathematical structure which is difficult to solve, and for which important properties, such as the existence of a global equilibrium, are very difficult to investigate. The authors discuss various solution techniques, but no definite algorithm is proposed.

Harker (1983) proposed a formulation, called the generalized spatial price equilibrium model, which attempts to tie together the spatial price equilibrium (to derive the demand for transportation) and the shipper/carrier equilibrium, in order to simultaneously predict the production and consumption of goods, freight rates, the shippers' routing of freight and the carriers' routing. The model does not consider intercarrier interactions but, it allows for different carrier rate-setting behaviours (fixed

rates, marginal cost pricing, etc.) and when using a general rate- reaction function it approximates the "gaming" that occurs between shippers and suppliers. Harker applies the marginal cost pricing variant of the formulation to the study of a large-scale problem of coal transportation in the U.S.

The national freight strategic planning model (Florian et al., 1986a; Crainic, Florian and Guélat, 1986a,b) is a system optimizing, explicit multiproduct, multimode network model. Flows are simultaneously assigned on the multimodal network using cost (either carrier operating costs or tarifs) and nonlinear delay functions, modeling infrastructure characteristics and congestion phenomena, computed both on the links and at the intermodal transfer points of the network. The model is embedded into an interactive-graphic system (Florian et al., 1986b) aimed at evaluating the impact of strategic scenarios (e.g. large variations in the composition or value of the demand, national policy changes, infrastructure investments, etc.) on the utilization of the national freight transportation system. Carrier services are locally approximated on each link for cost and delay computation purposes. Empty flows are induced by evaluating an O/D demand matrix for empty movements that is then considered as just another product to be transported. The system is actually used by a Brasilian transportation planning agency to evaluate strategic development scenarios for the Brasilian freight transportation system.

2.2 Research opportunities

First, we should stress that the study and development of models for multimodal, multicommodity intercity freight transportation is an art still in its infancy and many major areas of research have not yet been explored. This is particularly true in comparison with the urban transportation systems planning domain which has provided many of the principles and methodologies used so far in intercity freight transportation modeling. We

believe, in fact, that because of the higher complexity of intercity freight transportation systems, some bold and innovative concepts, departing from those developed for passenger transportation, are needed to achieve better formulations than those currently available.

One major research area concerns achieving increased realism in the representation of the behaviour of carriers and shippers and their relations. Shippers may indeed be viewed as competing non-cooperatively for transportation services, but their criteria should include not only cost (delivered price) but also delivery time and reliability. Carriers may be modeled as profit-maximizers while efficiently managing their networks, but some effort should be devoted to more realistically modeling their cost and tariff functions, as well as their routing decisions. In addition, carrier-carrier and shipper-carrier relations should be better represented. Thus, the competition or cooperation between carriers should be better addressed. Also, especially since deregulation, a carrier may propose different combinations of tariffs and levels of service for the same shipment. The insertion of these possibilities and of possible shipper reactions into a global model yields very interesting research problems.

The models of Harker (1986), Harker and Friesz (1986a,b) and Fisk (1986) attempt to address some of these complexities using game theory, market modeling techniques (Friedman, 1977) and integration of network models and spatial equilibrium models. Their results are theoretically very interesting and, although efficient solution procedures do not yet exist for a realistic setting of the models, they offer some very promising research and application opportunities.

The modeling of freight transportation systems results in mathematically complex problems and the design of efficient solution procedures for these problems forms an exciting research area. Exact, optimal algorithms should be sought. However, as optimal algorithms for problems of this

complexity tend to be cumbersome and slow, attention should also be devoted to the development of fast, efficient heuristics. Optimal algorithms may then be used to validate and bound the performance of the heuristics.

No formulation can capture all interaction possibilities, all the written and unwritten policies and rules, nor all the complexities of a real-life transportation system. So the possibilities offered by the integration of the models and algorithms into flexible planning tools aimed at scenario evaluation should continue to be investigated.

We agree with Daskin (1985) that, while almost all models of shipper-carrier interactions developed to date are short-term formulations (the network structure is given, prices and flows change instantaneously), adoption of a longer time frame is essential to the development of more realistic models of freight transportation systems. Such models could more easily incorporate such long term events as changes in shipper locations and carrier networks, entry and exit of carriers and shippers, and medium to long term carrier-shipper contracts stabilizing the costs and levels of service for some part of the flow. Note that the modeling of such carrier-shipper cooperation may require the development of new equilibrium concepts.

Both short or long time frame models should include some realistic formulation of the impact that fleet size constraints, backhauling, empty vehicle distribution and blocking have on routing and costs. This will require some innovative approximations and simplifications. Otherwise, the attempt to mix long term shipper-carrier interactions and short term carrier management considerations would most likely produce a huge model impossible to handle and validate, and asking for excessive computation times.

The stochastic characteristics of most real-life systems are notably absent from the models developed to date and their inclusion is an exciting

research area. Stochasticity of future demand, prices and travel times should be included in carrier-shipper interaction models. This is especially important for long time-frame models, but should not be overlooked in short time-frame models given the unreliability of available data.

Particular attention should be devoted to the development of true multimode, multicommodity models. Until now, most of the carrier-shipper models have been applied either to a single mode (usually rail) or to a single product (usually coal). The explicit consideration of multiple modes and commodities should increase the realism and utility of freight transportation models.

Finally, the scarcity and usual unreliableness of real data and the high cost of validation with real data once obtained and "cleaned", point to the need for validating and experimenting with models in a controlled, "laboratory" setting. This may be achieved using "market games" incorporating a given model or theory, where subjects play the roles of shippers and carriers. Such a game is currently under development (Lardinois et al. 1985a,b) for intercity multimodal passenger transportation. The development of similar games for freight transportation is an exciting research opportunity.

III - MODELS FOR PLANNING THE SUPPLY OF TRANSPORTATION SERVICES

Agencies supplying transportation services in an intercity freight transportation system generally operate complex networks consisting of numerous pick-up/delivery points, large classification/consolidation terminals and either physical (e.g. rail tracks) or conceptual (e.g. road or air lines) links connecting them. Some examples of organizations that follow this model are :

- rail companies offering several types of service ("modes") : direct, express, normal, etc.;

- truck companies offering the "less-than-truck-load" service with or without multitrailer convoys and with our without the TOFC (truck-on-flat-car) mode;
- container transportation on a multimodal network;
- freight transportation in developing countries where a central authority more or less controls the transportation system (at least for certain commodities).

A convenient way of classifying the various planning problems in this context is according to their planning horizon :

1. Strategic planning; long time frame, shapes the policy of the company.
   - allocation of investments;
   - physical network design and upgrading;
   - location of facilities;
   - broad routing and service decisions;
   - fleet sizing;
   - forecasting demand and market reactions;
   - pricing and costing policies.
2. Tactical planning; medium time frame, concerned with the efficient and rational allocation of existing resources to improve the overall performance of the system :
   - service network design - routes and characteristics of each transportation service (modes, frequency, etc.);
   - policies for classification of vehicles (into blocks) and consolidation of traffic (into vehicles) at terminals;
   - formation of vehicles (or blocks) into convoys;
   - traffic routing through the service network;
   - backhauling and empty vehicle distribution.
3. Operational (day-to-day) planning :
   - scheduling and routing of vehicles (for delivery/pick-up operations);
   - scheduling of crews;
   - dispatching rules, etc.

In this paper, we focus on models for the tactical level issues and only mention briefly some of the important work related to problems at other planning levels.

Some models for strategic planning were reviewed in the preceding section. Other pertinent models may be found in articles on network design problems (Magnanti and Wong, 1984; Friesz, 1985; Wong, 1984, 1985) and location and logistics problems (Daskin, 1985 and references therein). A review of demand estimation models may be found in Winston (1983) and Crainic, Nguyen and Picard (1984), while fleet sizing models are reviewed by Turnquist (1985). And, of course, there are numerous models from the fields of economics, management, and finance which may be used for strategic planning but are truly beyond the scope of this paper.

The problems of routing and scheduling vehicles do not really belong in a review of intercity multimodal freight transportation models. In addition, these problems have recently been thoroughly reviewed by Bodin et al. (1983), Golden (1984), Daskin (1985) and Golden and Baker (1985). Rousseau (1984) has recently published a review and state of the art on crew scheduling problems. Dejax and Crainic (1986) review models for empty freight vehicle transportation problems.

Tactical planning problems are crucial to operators of freight carrier companies because the efficient performance of the system depends upon their correct solution. But, these are complex problems usually involving several modes and multiple commodities. Moreover, due to the particular characteristic of freight transportation (freight is consolidated in vehicles, which may be classified into blocks, which are formed into convoys which move through predifined chanels), these problems and their associated policies have network-wide impacts and are strongly and complexly interconnected in both economic terms and in their space-time dimensions. Furthermore, trade-offs have to be reached between sometimes

conflicting decision criteria : costs, quality of service, etc. So, to capture these relations and trade-offs, global network models have been proposed. These models integrate the activities in terminals and on the lines, and generate and evaluate the network-wide impact of a large number of operational strategies with respect to some objective function, usually involving both operating costs and some measure of quality of service.

We now review some of the most significant contributions to this field.

3.1 Review of literature

The "Railcar Network Model" developped at the CIGGT at Queen's University by Petersen, Fullerton and others (1975) is a prime example of this class of models. The object of the model is to find the optimal traffic routing which minimizes total car delay : the sum of yard and line delays. In yards, the average delays are a function of the traffic flow through the yard, and are derived by means of queueing models. Similarly, Petersen's over-the-road model gives the average time to traverse a given link as a function of the train flow on that link. The number of trains to be run is determined from the traffic flow using a constant number of cars/train ratio. If the delay functions are all convex, the problem has the structure of a multicommodity flow problem with convex costs and it is solved by a primal-dual algorithm (Petersen, 1975) based on successive linearizations of the objective function. Although tested in the context of Canadian railways, the model is not actually in use.

Assad (1977, 1980b) suggests a network model that integrates the routing and train formation decisions. Its goal is to reduce the delays due to congestion in yards by means of direct trains bypassing the intermediate yards on their routes. Assad uses a route structure defining all the direct services for the problem at hand. The traffic travels on that structure,

connecting when the destination of the service is not the traffic destination. Every time a service reaches its destination, the traffic traveling on it goes through a classification prodecure. Different "fixed-charge" type formulas are suggested for the classification delay as a function of the yard throughput and the train composition. The resulting model has the structure of a mulicommodity mixed-integer flow problem with certain non-linearities in the objective function. An efficient solution technique has not yet been proposed for this model.

The blocking model of Bodin et al. (1980) aims to determine network-wide classification policies to minimize total delay : a sum of accumulation and connexion delays, processing time for cars and over-the-road travel time. Continuous variables give the number of cars shipped along specified paths and classified at specific yards, while integer variables specify the blocks formed at each yard. Bounds are imposed on the number of cars in a block and on the total number of cars processed through a yard. Additional constraints reflecting particular practices at the railroad under study further complicate the problem. So also does the form of the accumulation delay function : non-continuous piece-wise linear. This function is approximated by a continuous piece-wise linear function and the problem is solved by a heuristic based on successive relaxations of the original problem. Bodin and Berman (1979) describe the solution technique and the results of a case study involving 33 yards and a mixed integer problem with 1500 constraints, 1000 binary variables and 5000 continuous variables.

Powell and Sheffi (1983, 1986) and Powell (1986a) propose a network model for the "less-than-truckload" motor carrier load plan problem. Their network is composed of a large number of end-of-line terminals (300 to over 500 for a large U.S. company) a number of large breakbulk terminals (the primary sorting facility, 15 to 25 for the same company) and direct long-hauling trailer routes linking them. On this network, the load plan (the

direct services offered and the routing of traffic) which minimizes total transportation handling cost while satisfying level of service constraints in each market has to be determined. The problem is formulated as a mixed integer network design problem with Boolean variables for direct services and continuous variables for loaded and empty flows of trailers. Delays are not considered and service frequencies are not decision variables. Service requirements are handled through minimum service levels on certain markets. The algorithm proposed uses a local improvement heuristic which, using a specific sequencing logic, works from an initial network to drop or add links to the network. The flow is rerouted after each modification using a decomposition scheme and shortest path techniques (Powell and Koskosidis, 1984) on a modified problem. The empty balancing is a simple linear minimum cost network flow problem solved after the rerouting has been performed. This methodology has been integrated into an interactive system and is being applied to the case of a large U.S. LTL trucking company.

Crainic, Ferland and Rousseau (1984) propose a network model that integrates the tactical issues (train service and traffic routing, blocking and formation policies) in rail freight transportation. Its goal is the generation of global strategies to reduce the total operating and delay cost of the system. It uses a service network defining the feasible train services (routes, modes, etc.). For each traffic class, itineraries specify feasible journeys for the traffic : the sequence of classification terminals and the sequence of services linking them. Integer variables correspond to frequencies of service, while continuous variables are used for traffic flows. Classification delays are a function of the yard throughout (via queueing models) and the particular block the cars are sorted into; connexion delays are a function of the frequency, capacity and the type (regular or following a certain probability distribution) of service chosen; over-the-road delays are a function of the total train flow on the link and track configuration. The model has the structure of a

nonlinear, mixed integer, multimode, multicommodity flow problem (in arc-chain formulation) minimizing an objective which combines operating costs, delay costs and penalty costs for service or capacity requirements. The O/D empty demand is exogenously computed, empty cars being then considered as another commodity. Crainic and Rousseau (1986) present the multimode generalization of the model and detail the algorithm used to solve it. It is a decomposition procedure that alternates between modifying the frequencies while holding the flows fixed and optimizing the flows (via decomposition and descent procedures) while holding the frequencies fixed. A column generation procedure builds itineraries by a shortest-path-like method using generalized costs combining marginal transportation costs and service considerations. This approach has been successfully applied to problems from the Canadian (Crainic, 1984) and French (Crainic and Nicolle, 1986) railways. An interactive-graphic planning system is actually being built (Crainic and Mondou, 1986) based on this methodology.

Roy (1984, 1985) has successfully adapted this methodology to the multimode (various truck sizes and ownerships, plus TOFC) LTL trucking problem. He uses the same modeling and algorithmic framework but employs the various delays in terminals and on the roads to compute transportation time means and variances to evaluate, through penalties in the objective function, the performance on each route as compared with predefined service requirements. The empty movements are balanced through a linear minimum cost network flow problem once the main algorithm stops. Several applications have been done with data from large LTL Canadian truck companies.

3.2 Research opportunities

One important area of research is concerned with greater model accuracy. Tactical models are usually complex structures where most of the terms, such as delays, costs, etc., are derived from behaviour and performance analysis of subsystems : rail links, breakbulk terminals, rail yards,

etc. Despite the amount of work published in this area, especially in the rail literature (see, for example, the reviews of Assad 1980a or Crainic, Nguyen and Picard, 1984), work still has to be done on the accurate modeling of subsystems for inclusion in larger, general network models. One area that should not be overlooked is the formulation of more precise and complex models for the subsystems together with some innovative and creative approximations of their outputs for inclusion in the network model. The work of Powell (1986b) and Crainic and Gendreau (1986), on estimating terminal delays using approximate (but derivable) formulas derived from queueing processes, represent worthy achievements in this direction.

A second important research area concerns the development of efficient solution procedures. The models usually involve mathematical structures which are difficult to solve : mixed variables, fixed costs, concave cost functions and other nonlinearities, large scale dimensions, multiple solutions etc. Exact, optimal algorithms are therefore generally cumbersome and much too inefficient to be of practical, industrial use and it is thus important to develop fast and efficient heuristic algorithms. These heuristics, however, have to be validated by comparing their results with a, hopefully, tight bound. So, Lamar, Sheffi and Powell (1984) present interesting results for a class of problems derived from their LTL planning model, where the existance of direct services (0-1 variables) is decided. No such results are available yet for the other models, especially for those where service frequencies (general integer variables) are involved. The theoretical study of the models and the development of exact algorithms to compute these bounds form an exciting research opportunity.

Empty movements of vehicles contribute greatly to operating costs. Incorporating empty movement planning into tactic and strategic models thus presents not only a very interesting research opportunity but also significant potential savings when applied (Dejax and Crainic, 1986).

Stochasticity (at least for transportation and through-terminal times) and fleet size constraints are two aspects of real-life situations

that should be included into tactical planning models. Both elements, and more specially the fleet constraints, have the potential to greatly complicate the models, presenting researchers with some very interesting modeling and algorithmic challenges.

As in the previous section, no tactical model can represent all situations, rules and policies and answer all queries. It is therefore important to develop efficient, flexible and "friendly" planning tools, which, besides the models and algorithms, should include a data bank and interactive-graphics capabilities. The systems developped by Kornhauser (1982) and Crainic and Mondou (1986) represent two interesting developement directions in this area.

IV - GENERAL COMMENTS

These are general remarks that apply to all problems and models reviewed in this paper.

First, in freight transportation, a real problem usually lies (or should lie) behind each model. This raises the problem of unreliable and often unavailable data. Better procedures for building, cleaning and validating data sets are needed, together with methods for increasing the robustness of models and algorithms to the effects of "dirty" data.

Secondly, it would be useful to have some standard test problems and criteria by which to judge the efficiency of models and algorithms. These standards would also facilitate comparisons between methods, placing them on a more scientific basis.

Finally, we want to emphasize, with Hendrickson (1985), and Golden and Baker (1985) amongst others, that recent advances in computer science (microcomputers, graphics, interactive systems, etc.), artificial intelligence (expert systems) and decision support systems open up new and exciting research possibilities for transportation science. So, it is

possible now to built comprehensive interactive-graphic planning systems that run on micro-computers (e.g., the work of Florian et al., 1986) and thus, to put impressively powerful computational (hardware) and planning (software) means within easy financial reach of practically every size of organization (carrier, shipper, etc.) involved in the transportation system. Also the combination of traditional optimization algorithms and expert system techniques may yield very interesting results.

We have thus completed our survey of current and future research issues in intercity freight transportation analysis with emphasis on two major study areas : the predictive analysis of the systems and models for the planning of transportation services. A first conclusion is that there already exist interesting models and planning systems that may help analyze and solve a large a range of transportation problems. Secondly, because freight transportation modeling may be considered still in its infancy, many major area of research have not been yet explored. We have therefore identified and briefly discussed a number of very interesting research opportunities.

BIBLIOGRAPHY

ASSAD, A.A. (1977) "Modelling Rail Freight Management", Ph.D. Thesis, Sloan School of Management, Massachusetts Institute of Technology, Cambridge, MA, U.S.A.

ASSAD, A.A. (1980a) "Models for Rail Transportation", Transportation Research A 14A, 205-220.

ASSAD, A.A. (1980b), "Models of Rail Networks : Toward a Routing/Make-up Model", Transportation Research B 14B, 101-114.

BODIN, L.D. and BERMAN, L.J. (1979) "A Model for the Blocking of Trains", Final Report No. RMGT-FRA-1-79, College of Business and Management, University of Maryland at College Park.

BODIN, L.D., GOLDEN, B., ASSAD, A. and BALL, M. (1983) "The State of the Art in the Routing and Scheduling of Vehicles and Crews", Computers and Operations Research, 10, 2, 63-211.

BODIN, L.D., GOLDEN, B.L., SCHUSTER, A.D. and ROMIG, W. (1980) "A Model for the Blocking of Trains", Transportation Research B 14B, 115-120.

BRONZINI, M.S. (1980a) "Evolution of a Multimodal Freight Transportation Network Model", in Proceedings of the 21st Annual Meeting, Transportation Research Forum, 475-485.

BRONZINI, M.S. (1980b) "Freight Transportation Energy Use", U.S. D.O.T. Report No. DOT-TSC-OST-79-1, Vols I and II.

BRONZINI, M.S. and SHERMAN, D. (1983) "The Rail Carrier Route Choice Model", Transportation Research A 17A, 6, 463-469.

BRONZINI, M.S., HERENDAN, J.H., MILLER, J.H. and WOMER, N.K. (1974) "A Transportation-Sensitive Model of a Regional Economy", Transportation Research 8, 45-62.

CACI Inc. (1980) "Transportation Flow Analysis : The National Energy Transportation Study (NETS)", 3 vols., U.S. D.O.T. Report No. DOT-OST-P-10 (29-32).

CHARLES RIVER ASSOCIATES INC. (1981) "An Analysis of the Interaction of the Coal and Transportation Industries in 1990", Report No. 494. Prepared for the U.S. Department of Energy, Boston.

CRAINIC, T.G. (1982) "Un modèle de planification tactique pour le transport ferroviaire des marchandises", Ph.D. Thesis, département d'informatique et de recherche opérationnelle, Université de Montréal, publication #247, Centre de recherche sur les transports, Université de Montréal.

CRAINIC, T.G. (1984), "A Comparison of Two Methods for Tactical Planning in Rail Freight Transportation", in : Operational Research '84, J.P. Brans (Ed.), Elsevier Publishers, North-Holland, 707-710.

CRAINIC, T.G. and GENDREAU, M. (1986), "Approximate Formulas for the Computation of Connection Delays under Capacity Restrictions in Rail Freight Transportation", Proceedings of the "Fourth World Conference on Transport Research", Vol. 2, 1142-1155, May 1986, Vancouver, Canada.

CRAINIC, T.G. and MONDOU, J.-F. (1986), "An Interactive Graphic Planning System for Freight Transportation Networks", ORSA/TIMS Joint National Meeting, Miami, October 1986.

CRAINIC, T.G. and NICOLLE, M.C. (1986), "Planification tactique du transport ferroviaire des marchandises : quelques aspects de modélisation", Proceedings of "1st International Congress in France : Industrial Engineering and Management", AFCET-CEFI-GCI, 161-174.

CRAINIC, T.G. and ROUSSEAU, J.-M., (1986) "Multicommodity, Multimode Freight Transportation : a General Modeling and Algorithmic Framework for the Service Network Design Problem", Transportation Research B 20B, 3, 225-242.

CRAINIC, T.G., FERLAND, J.A. and ROUSSEAU, J.-M. (1984) "A Tactical Planning Model for Rail Freight Transportation", Transportation Science 18, 2, 165-184.

CRAINIC, T.G., FLORIAN, M. and GUÉLAT, J. (1986a), "O.R. Tools for Strategic Planning of National Freight Systems : Modeling", Centre de recherche sur les transports, Université de Montréal.

CRAINIC, T.G., FLORIAN, M. and GUÉLAT, J. (1986b), "O.R. Tools for Strategic Planning of National Freight Systems : Algorithms", Centre de recherche sur les transports, Université de Montréal.

CRAINIC, T.G., NGUYEN, S. and PICARD, G. (1984) "Selected Review of Methodologies in Freight Transportation Planning", publication #333, Centre de recherche sur les transports, Université de Montréal.

DASKIN, M.S. (1985) "Logistics : An Overview of the State of the Art and Perspectives on Future Research", Transportation Research A 19A, 5/6, 383-398.

DEJAX, P.J. and CRAINIC, T.G. (1986), "A Review of Empty Flows and Fleet Management Models in Freight Transportation", Transportation Science 21(4).

FISK, C.W. (1986) "A Conceptual Framework for Optimal Transportation Systems Planning with Integrated Supply and Demand Models", Transportation Science 20, 1, 37-47.

FLORIAN, M. (1983), "Nonlinear Cost Network Models in Transportation Analysis", NETFLOW'83, International Workshop on Network Flow Optimization Theory and Practice, publication #287, Centre de recherche sur les transports, Université de Montréal.

FLORIAN, M. and GAUDRY, M. (1980) "A Conceptual Framework for the Supply Side in Transportation Systems", Transportation Research B 14B, 1-8.

FLORIAN, M., SENÉCAL, L., NGUYEN, S. and CRAINIC, T.G. (1986a), "A Multi-product Multimode Freight Assignment Model for National Transportation Planning", TIMS/ORSA Joint National Meeting, Los Angeles.

FLORIAN, M., CRAINIC, T.G., GUÉLAT, J. and BABIN, A. (1986b), "FRET : An Interactive Graphic System for Strategic Planning of Freight Transportation at the National and Regional Level", Publication #495, Centre de recherche sur les transports, Université de Montréal.

FRIEDMAN, J.W. (1977), "Oligopoly and the Theory of Games", North-Holland, New York.

FRIESZ, T.L. (1985) "Network Equilibrium Design and Aggregation", Transportation Research A, 19A(5/6), 413-427.

FRIESZ, T.L. and MORLOK, E.K. (1980) "Recent Advances in Network Modeling and their Implications for Freight Systems Planning", Proceedings of Transportation Research Forum 21, 513-520.

FRIESZ, T.L., GOTTFRIED, J.A. and MORLOK, E.K. (1986) "A Sequential Shipper-Carrier Network Model for Predicting Freight Flows", Transportation Science 20(2), 80-91.

FRIESZ, T.L., TOBIN, R.L. and HARKER, P.T. (1983) "Predictive Intercity Freight Network Models : the State of the Art", Transportation Research A 17A, 2, 409-417.

FRIESZ, T.L., GOTTFRIED, J.A., BROOKS, R.E., ZIELEN, A.J., TOBIN, R., and MELESKI, S.A., (1981) "The Northeast Regional Environmental Impact Study: Theory, Validation and Application of a Freight Network Equilibrium Model", Report No. ANL/ES-120, Argonne National Laboratory, Argonne, IL.

GOLDEN, B.L. (1984) "Introduction and Recent Advances in Vehicle Routing Methods" in Transportation Planning Models, M. Florian, ed., North-Holland.

GOLDEN, B.L. and BAKER, E.K. (1985) "Some Thoughts on Future Directions in Logistics Research", National Science Foundation Conference on Transportation Research, Evanston, Illinois, March 20-22.

HARKER, P.T. (1983) "Prediction of Intercity Freight Flows : Theory and Application of a Generalized Spatial Price Equilibrium Model", Ph.D. Dissertation, University of Pennsylvania, Philadelphia.

HARKER, P.T. (1986), "Alternative Models of Spatial Competition", Operations Research 34, 3, 410-425.

HARKER, P.T. and FRIESZ, T.L. (1982) "A Simultaneous Freight Network Equilibrium Model", Congressus Numerantium 36, 365-402.

HARKER, P.T. and FRIESZ, T.L. (1986a), "Prediction of Intercity Freight Flows I : Theory", Transportation Research B 20B, 2, 139-153.

HARKER, P.T. and FRIESZ, T.L. (1986b), "Prediction of Intercity Freight Flows II : Mathematical Formulations", Transportation Research B 20B, 2, 155-174.

HENDRICKSON, C. (1985) "Research in Transportation System Characteristics and Operations", Transportation Research A 19A, 5/6, 367-369.

JONES, P.S. and SHARP, G.P. (1979) "Multi-Mode Intercity Freight Transportation Planning for Underdeveloped Regions", in Proceedings 20th Annual Meeting, Transportation Research Forum.

KORNHAUSER, A.L. (1982) "Examples of Corporate Distribution and Transportation Planning Using the Princeton Transportation Network Model and Graphic Information System", Princeton University.

KORNHAUSER, A.L. (1985) "A Very Large Transportation Network Interactive Computer Graphic Information System and Problem Solver", ORSA/TIMS Joint National Meeting, Boston, May 1985.

KORNHAUSER, A.L., HORNUNG, M., HAZONY, Y. and LUTIN, J. (1979) "The Princeton Railroad Network Model : Application of Computer Graphics in the Analysis of a Changing Industry", presented at the 1979 Harvard Graphics Conference, Transportation Program, Princeton University, Princeton, NJ.

KRESGE, D.T. and ROBERTS, P.O. (1971) "Systems Analysis and Simulation Models", in Techniques of Transport Planning, John R. Meyers, ed., Vol. 2, Brookings Institute, Washington, D.C.

LAMAR, B.W., SHEFFI, Y. and POWELL, W.B. (1984) "Bounding Procedures for Fixed Charge, Multicommodity Network Design Problems", Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, MA.

LANSDOWNE, Z.F. (1981) "Rail Freight Traffic Assignment", Transportation Research A 15A, 183-190.

LARDINOIS, C., CORMIER, M. and ROY, S. (1985a) "JET-SET : Jeu Éducatif en Transport/Simulation for Education in Transportation. Part 1 - Operation and Rules of the Game", publication #405-E, Centre de recherche sur les transports, Université de Montréal.

LARDINOIS, C., D'AVIGNON, J. and HIROU, C. (1985b) "JET-SET Jeu Éducatif en Transport/Simulation for Education in Transportation. Synthesis", publication #407-E, Centre de recherche sur les transports, Université de Montréal.

MAGNANTI, T. and WONG. R.T. (1984) "Network Design and Transportation Planning : Models and Algorithms", Transportation Science 18, 1-55.

MANHEIM, M.L. (1980) "Understanding 'Supply' in Transportation Systems", Transportation research A 14A, 19-136.

MARCOTTE, P. (1986) "Network Design Problem with Congestion Effects : a Case of Bilevel Programming", Mathematical Programming 34, 142-162, North-Holland.

McGINNIS, L.F., SHARP, G.P. and DAVID YU, H.C. (1981) "Procedures for Multi-State, Multi-Mode Analysis : Vol. IV, Transportation Modeling and Analysis", U.S. D.O.T. report No. DOT-OST-80050-17/V.IV.

MOAVENZADEH, F., MARKOW, M.J., BRADEMEYER, B.D. and SAFWAT, K.N.A. (1983) "A Methodology for Intercity Transportation Planning in Egypt", Transportation Research A 17A, 6, 481-491.

PETERSEN, E.R. and FULLERTON, H.W. (eds.) (1975) "The Railcar Network Models", Canadian Institute of Guided Ground Transport, report No. 75-11, Queen's University, Kingston, Ontario.

POWELL, W.B. (1986a) "A Local Improvement Heuristic for the Design of Less-than-Truckload Motor Carrier Networks", Transportation Science 20, 4, 246-257.

POWELL, W.B. (1986b), "Approximate, Closed Form Moment Formulas for Bulk Arrival, Bulk Service Queues", Transportation Science 20, 1, 13-23.

POWELL, W.D. and KOSKOSIDIS, J. (1984) "Shipment Routing Algorithms for Less-than-Truckload Trucking Networks", Department of Civil Engineering, Princeton University.

POWELL, W.B. and SHEFFI, Y. (1983) "The Load Planning Problem of Motor Carriers : Problem Description and a Proposed Solution Approach", Transportation Research A 17A, 6, 471-480

POWELL, W.B. and SHEFFI, Y. (1986), "Design and Implementation of an Interactive Optimization System for Network Design in the Motor Carrier Industry", working paper EES-86-B, Department of Civil Engineering, Princeton University.

ROBERTS, P.O. (1966) "Transport Planning : "Models for Developing Countries", Ph.D. Dissertation, Civil Engineering Department, Northwestern University, Evanston, IL.

ROUSSEAU, J.-M. (1984) "Crew Scheduling Methods in the Operation and Planning of Transportation Systems", in Transportation Planning Models, M. Florian, ed., North-Holland.

ROY, J. (1984) "Un modèle de planification globale pour le transport routier des marchandises", Ph.D. Thesis, École des Hautes Études Commerciales de Montréal.

ROY, J. (1985) "A Tactical Planning Model for Motor Carrier Operations", presented at the TIMS/ORSA Joint Meeting, Boston, May 1985.

SHARP, G.P. (1979) "A Multi-Commodity, Intermodal Transportation Network Model", in Proceedings 20th Annual Meeting, Transportation Research Forum.

SHARP, G.P. and JONES, P.S. (1981) "Procedures for Multi-State, Multi-Mode Analysis : Vol. I, Executive Summary", U.S. D.O.T. report No. DOT-OST- 80050-17/V.I.

TURNQUIST, M.A. (1985) "Research in Transportation System Characteristics and Operations", Transportation Research A 19A, 5/6, 357-366.

WARDROP, F. (1952), "Some Theoretical Aspect of Road Traffic Research", in : Proceedings of the Institute of Civil Engineers", Part II, Vol. 1, 325-378.

WINSTON, C. (1983) "The demand for freight transportation : models and applications", Transportation Research A 17A, 6, 419-427.

WONG, R.T. (1984) "Introduction and Recent Advances in Network Design : Models and Algorithms", in Transportation Planning Models, M. Florian, ed., North-Holland.

ACKNOWLEDGEMENTS

This research has been supported in part by a grant from Transport Canada through the Transport University Programs. I wish also to thank two anonymous referees whose comments have allowed for a much improved presentation of this paper.